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A SCALING LAW FOR FRAGMENTING CYLINDRICAL WARHEADS

by

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ABSTRACT. Existing scaling laws for the prediction of fragment velocities from cylindrical warheads are examined, and a new law is proposed. Tests of the new law are shown, using the best known fragment velocity data. The new law is used for correlating previously unpublished data on length-to-diameter ratio effects and on the behavior of axially hollow warheads. Possibilities for profitable future investigations are outlined in studies of length-to-diameter ratio effects, and in the use of modifications of the new scaling law for correlating "open-face-sandwich" plate velocity data and fragment velocities from spherical warheads.

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FOREWORD

This report covers a review of scaling laws for predicting fragment velocities for metal and explosive warheads. It has been supported in the Warhead Supporting Research Group effort at the Naval Weapons Center under Naval Air Systems Command Task No. A35-350/216/69-F17-353-501 Warhead Supporting Research, Surface Targets. This is a summation of effort accumulating over the past several years. Its culmination is a new scaling expression.

This report was reviewed for technical accuracy by C. D. Lind and H. M. Platzek.

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INTRODUCTION

The traditional symbol for ordnance is a spherical cannon ball with burning fuse; however, a warhead or a gun projectile is a concentrated package of energy which must be rapidly translated through a fluid medium, and this is done more effectively if it is shaped as an elongated cylinder that is propelled end-on. Consequently most warheads are elongated bodies of revolution and most can be fairly represented as cylinders. Warheads that are intended to be effective through fragmentation generally have an external steel or other metal shell that is filled with high explosive, the latter being detonated at one end (Colonel Shrapnel embedded nuts and bolts in the explosive filling of his gun projectiles, but this arrangement is not very effective, and went out of style after World War I). So for study purposes a warhead can be simplified and represented as a hollow steel cylinder with length-to-diameter ratio (L/D) around 2 1/2, more or less, and filled with explosive, end-detonated. The desired scaling law for such a system will enable the prediction of the initial velocity of the metal fragments before they are slowed by atmospheric drag, for any explosive, any metal, and any combination of dimensions.

In considering the interior ballistics of guns, use is made of a "power constant" to characterize the propellant, and of the ratio of the weights of powder and projectile, these being general scaling parameters which are to be combined with gun chamber volume and bore length to calculate the muzzle velocity for a particular case (Ref. 1).

In the interior ballistics of rockets a similar situation pertains. The simplified expression for determining the initial velocity of the rocket projectile after propellant burnout, in the airdrag and gravity free condition, shows this initial velocity to be directly proportional to a constant which characterizes the propellant and to a logarithmic function of the ratio of propellant weight to rocket weight after burnout (Ref. 2).

An expression involving similar parameters for correlating the fragment velocities of cylindrical warheads was proposed by Gurney (Ref. 3) in 1943. In it the initial fragment velocity is stated to be directly proportional to a constant that is determined by the nature of the high explosive composition (this constant being $\sqrt{2E}$ where E represents the contribution to kinetic energy of unit weight of the explosive), and a function $\sqrt{R}$ of the ratio of weight of explosive charge to weight of metal jacket (C/M). Gurney tested his expression by using it to correlate the fragment velocity data then available for TNT loaded ordnance, and said that "....this expression is found to agree with the experimental data fairly well over the whole range from C/M = 0.06 to C/M = 5.6." In doing this, he assigned to TNT the value of 8,000 ft/sec for $\sqrt{2E}$; reducing this value to energy units, he found E = 715 cal/g, and compared it to the most nearly comparable calorimetric value that he could find, 890 cal/g. His Fig. 2 which plots the experimental data in comparison with the line predicted by the equation for ordinates of initial velocity and abscissae of his function of C/M shows by inspection that the slope of the line (which is determined by $\sqrt{2E}$) is just a little too great for the items of lower C/M and just a little too small for those with the highest values. Despite these minor discrepancies which apparently caused Gurney to be somewhat less than highly enthusiastic about the success of his correlation, his work has served as the basis for warhead development in the United States for the past 25 years.

Another expression for scaling fragment velocities of cylindrical warheads has recently come to the writer's attention. Held (Ref. 4), of the Boelkow Apparatebau G.m.b.H., Schrobenhausen, Germany, published in "Explosivstoffe" a serial entitled, "Splitterballistik" (Fragment Ballistics), which gives the equation following, attributed to Lukanow and Molitz (Ref. 5) (and reproduced here in symbols mostly defined in the preceding paragraphs):

$$\eta EC = aM + \frac{1}{2} (M + \varepsilon C) V_o^2 \tag{1}$$

where η is a constant denoting the energy efficiency of the explosive, a is a quantity indicating the energy requirement for deforming and fracturing a unit mass of the metal case, while ε is an "Equalization Factor" (Ausgleichsfaktor), evidently related to the proportionate mass of the detonation product gases which on the average attain the same velocity as the fragments of the case. By setting $\eta = 1$ and $a = 0$, and then rearranging and comparing with Gurney's formula it appears that this relation is the same as Gurney's when $\varepsilon = 1/2$. The use of an efficiency factor for the explosive is not essential as long as the specific energy factor E is determined empirically from fragment velocity measurements, but its use might be beneficial in reminding warhead designers that generally less than 60% of the thermodynamically determined "detonation energy" of an explosive can be converted into kinetic energy of fragments. The energy necessary for deformation and fragmentation of the metal has usually been considered negligible. Interestingly enough, when, in the Lukanow and Molitz Equation (1) ε is set at 3/5, and when $\eta = 1$, and $a = 0$, this equation becomes identical with Gurney's equation for the velocity of fragments from a spherical warhead.

Henry (Ref. 6) derives a scaling law, stating in his abstract that "A slight elaboration based on an approximate equation-of-state for the explosive products and a more accurate distribution of the detonation gas is shown to produce results not markedly superior to the Gurney postulate."

The features of these scaling laws that have been most successful and which should be continued in use are:

1. The use of an empirically determined constant to represent the performance of the propellant or explosive.

2. The ratio of the weight of propellant or explosive to the weight of metal or other matter that is projected. (For warheads this is C/M).

On the other hand, it is the writer's opinion that the function proposed by Gurney $\left[\frac{C/M}{1 + C/2M} \right]^{0.5}$ can be replaced by another function of C/M with some improvement. It is the main object of this report to propose a function for this purpose and to show the manner and degree in which it may be expected to improve the correlation of warhead fragment velocity data.

WHAT ARE THE CHARACTERISTICS OF A GOOD SCALING LAW?

Boiled down until practically nothing useful is said, the ideal scaling law should relate any case material and any explosive, in any diameter of explosive and case thickness and any L/D ratio, to the initial velocity of its case fragment, with no need for "variable constants" which are dependent upon any of the other parameters of the scaling law expression.

In all of the scaling laws for cylindrical warheads that are known to the writer, the explosive diameter and case thickness in effect are combined with the densities of explosive and case material and used as the C/M ratio or some equivalent of it, which is understood as the ratio of the masses of explosive and metal or other case material in a transverse section of the cylinder of unit axial length, all at a location far enough from the detonation end so that the detonation has run up to substantially full strength, and far enough from the downstream end so that release wave effects from that end are not important. This scaling factor has generally been highly effective.

The fragment velocity is controlled even more strongly by the quality of the explosive, and all known scaling laws use a parameter representing this quality, which typically has the units of velocity. However, there has been no rationale proposed which successfully permits the accurate calculation of this parameter from thermal and chemical data on the explosive. Consequently, it has been universally necessary to determine the constant for each explosive from experimental determinations of fragment velocities, using the scaling law "in reverse."

The general experience to date with this scaling law factor has not been fully satisfactory; explosive quality constants reported from different laboratories for the same explosive have not been in complete agreement, nor have constants determined at one value of C/M been found entirely satisfactory for use at a C/M value that is markedly different. Thus, one can say that a good scaling law, when used "in reverse" to determine the explosive constant for one unchanging explosive when tested under a wide range of C/M values should yield the same number, with only experimental error. A trend of the explosive constant which correlates with C/M, indicates the appearance of an undesirable "variable constant" and should be avoided if possible.

The degree of invariance of the explosive constant can be used as a criterion of scaling law effectiveness; and will be so used in this report. Obviously, this criterion can only be effective when the scatter in the data is less than the indicated trend of the data with changing C/M. Accurately determined fragment velocities determined for a wide range of C/M conditions are required, and such data are hard to come by.

A PROPOSED SCALING LAW

The scaling law proposed here may be expressed as:

$$V_o = V_c L^{0.5} \tag{2}$$

where V_o is the initial fragment velocity, V_c is the velocity characteristic of the explosive, and L represents the quantity in (1 + C/M). This expression is analogous to the rocket propulsion equation given in Ref. 2 (except for the exponent), which may be expressed as:

$$V_b = V_e \ln (1 + W_p/W_b) \tag{3}$$

where V_b is the burnt velocity of the rocket, V_e is the exit velocity of the propellant gases from the nozzle (and may be divided by the gravitational constant g to get the Specific Impulse of the propellant in lb-sec/lb), W_p is the propellant weight, and W_b is the burnt weight of the rocket after all the propellant has been consumed.

The quantity V_o in Eq. (2) is ambiguous until its method of determination is stated. The cylinder expansion test, observing the motion of the external surface of an explosively expanded metal cylinder, may or may not indicate the cessation of acceleration before the metal cylinder ruptures, but in any case the observation is terminated by obscuring gases venting through cracks in the cylinder and gives no indication of possible further fragment acceleration by the drag of venting gases. The observation of mean fragment velocities by timing impacts at two or more velocity screens and then extrapolating back to the velocity at the time and place of "first light" is subject to other uncertainties, mainly involving questions regarding the drag coefficients of fragments of different sizes and the distribution of impact times at the down-range impact points. The X-ray method of observation should be capable of determining the metal velocity at the time when the last accelerating force has fallen to a value equal to the decelerating force of airdrag, but the attainment of adequate acceleration/deceleration resolution may be very difficult. The following discussions of this paper will ignore these differences, as being of minor consequence to the consideration presented.

The quantity V_c in Eq. (2) will be referred to here as the "Characteristic Velocity" of the explosive. As may be seen by comparing Eq. (2) and (3), it is analogous to the "Gas Velocity" of a rocket propellant, and in consequence it may be converted to an analog of the "Specific Impulse" of a rocket propellant. (As will be shown, the Characteristic Velocity of Composition B is about 8,293 ft/sec, which corresponds to a quasi-specific impulse of 257.5 lb-sec/lb, a value which appears not unreasonable in comparison with the specific impulse values for good propellants.) In this view, the Characteristic Velocity is a direct measure of the impulse-delivering capability of an explosive when projecting fragments of a cylindrical warhead.

Just as the Characteristic Velocity is a measure of the impulse-imparting capability of an explosive, so is the square of the Characteristic Velocity a measure of its energy-transferring capability. Let us assume that $V_c^2/2$ is equivalent to the kinetic energy-imparting capacity of unit weight of the explosive, and that C is the weight of explosive in a given cylindrical device jacketed by metal weighing M. Then the transferable energy before detonation is $CV_c^2/2$ and the kinetic energy of the metal fragments after detonation is $MV_o^2/2$. Using Eq. (2), squaring and multiplying by M/2, we have:

$$MV_o^2/2 = MV_c^2/2L \tag{4}$$

The fraction F of chemical energy that is converted into fragment kinetic energy is then:

$$F = \frac{MV_o^2/2}{CV_c^2/2} = \frac{MV_c^2L}{CV_c^2} = \frac{ML}{C} \tag{5}$$

Table 1 shows values of this fraction F at several values of C/M, from which it may be seen that at very low values of C/M the kinetic energy of the fragments tends toward a value equal to the kinetic energy-imparting capacity of the explosive.

TABLE 1. Values of the Fraction F of Transferable Energy Converted to Kinetic Energy of Fragments.

C/M	L	F
10.0	2.397	0.2397
1.0	0.6931	0.6931
0.10	0.09531	0.9531
0.01	0.009950	0.9950

In formulating his scaling law, Gurney (Ref. 3) defined E, not as the calorimetric energy content of the explosive, but as "....the contribution to the kinetic energy made by the detonation of each unit mass of ....explosive....." This distinction has been missed by many users of the Gurney equation; the writer missed it for years, and only on a recent re-reading of Gurney's report was the clarity of his expression of this point appreciated. It can be readily seen, then, that Gurney's quantity E and the kinetic energy-imparting term $V_c^2/2$ that was postulated in the previous paragraph are analogous, just as V_c in Eq. (2) is analogous to Gurney's $\sqrt{2E}$. Also, the Gurney scaling law can be used just as Eq. (2) was used to determine the fraction of the transferable energy that appears in the kinetic energy of the fragments, and with closely similar results. The variation of this fraction with changing C/M as shown in Table 1 indicates that at very heavy loading of the explosive (small values of C/M) the transferable energy appears mostly as kinetic energy of the fragments while very light loading of the explosive results in the greater part of the energy appearing in the kinetic energy of the gaseous detonation products. One further consequence of this line of reasoning is that any set of experiments which results in the calculation of a Gurney E or in a value of $V_c^2/2$ which corresponds to an energy value equal to or greater than the calorimetrically determined detonation energy of the explosive, clearly points to either a defect in the scaling law or to experimental error; the state of equality could only be found in a thermodynamically reversible process, and a finding of greater kinetic than thermal energy would violate conservation of energy requirements. It is also evident that the calculation of the value of E or of $V_c^2/2$ for any particular explosive from its calorimetric detonation energy is an involved matter, and it should not be surprising that it has not yet been accomplished.

To facilitate the use of Eq. (2), a table of value of L and of $L^{0.5}$ for various values of C/M is included in this report as an Appendix. This Appendix gives values of a Conversion Factor which permits one to convert values of $L^{0.5}$ to values of Gurney's $\sqrt{R}$. It is evident in the figure that values of $L^{0.5}$ and of $\sqrt{R}$ may be used interchangeably with less than 1% error in range of C/M values below 0.5, and that the difference between them does not become greater than 5% until C/M increases beyond 3.0.

THE EXPERIMENTAL DATA

SOLEM AND SINGLETON'S DATA

In 1953 Solem and Singleton published in NAVORD Report No. 2768 (Ref. 7) a set of fragment velocity determinations covering an extraordinarily wide range of values of C/M. Cylinders of Composition B, 2 inches in OD were encased in steel having wall thicknesses ranging from 0.03125 to 0.250 inch, and in aluminum cases ranging from 0.002 to 0.500 inch thick. Explosive and case were of two lengths, 5 and 12 inches, and a helium atmosphere was used in some experiments. Initial fragment velocity was defined as the case particle velocity at the time of fracture and venting of detonation products, and was measured by the streak camera method with exploding wire illumination. Correction was made for fragment projection angle using the Taylor relation.

In their summary, Solem and Singleton state, "It has been demonstrated that the Gurney formula does not appear valid when very thin cases are considered." Although they do not comment directly on the point, it is evident that the agreement between their results from aluminum and steel is good, and that each can be represented by its density in determining C/M values. Slightly greater velocity values were found for the 12-inch-long explosive bodies than for those 5 inches long, in the two cases where comparison can be made. They carefully examined their experimental method and concluded that their velocities were measured to an accuracy of better than 3 to 4%.

Averaged results for initial fragment velocities presented in their Table IV are used for calculating $\sqrt{2 E}$ by the Gurney equation and V_c by Eq. (2) in this report. These values, characteristic of Composition B, are plotted against the corresponding values of C/M in Fig. 1.

The values of Gurney's $\sqrt{2 E}$ are fairly consistent at the lower values of C/M (where, fortunately, the practical problems of warhead design are nearly all found), but at the higher values of C/M they become unreasonably high as Solem and Singleton concluded. Donna Price (Ref. 8) has given the value of 1,119 cal/g for the thermal detonation energy of Composition B, which corresponds to a value of $\sqrt{2E}$ of 10,039 ft/sec, so the three highest values on the Gurney curve are patently incorrect.

The curve of V_c values calculated by Eq. (3) is not a horizontal line, such as one would wish to find. It can be shown that this same experimental data can be reduced to values of V_c which may be represented by a horizontal line by changing the exponent of Eq. (2) from 0.5 as used here to 0.565.

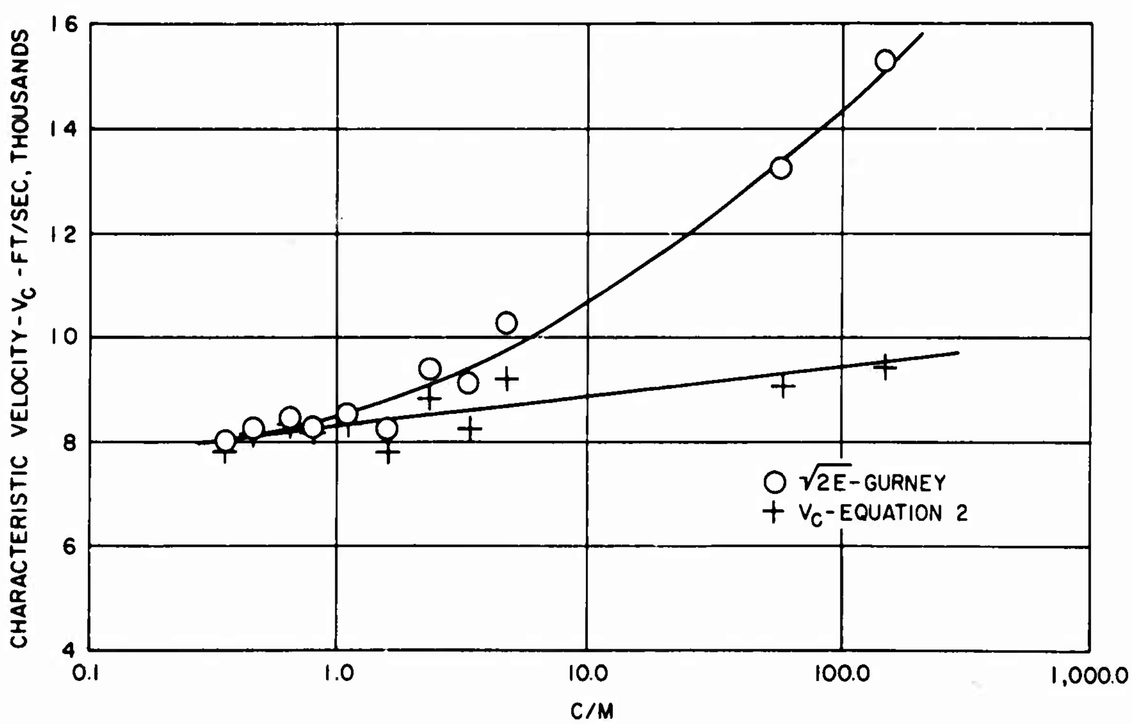

FIG. 1. Constants Characteristics of Composition B.

GURNEY, HELD, AND HENRY

The fragment velocity data that are cited by Gurney are a meager lot indeed. Five data points were from another laboratory, determined on 2-inch ID cylinders, one point being replicated and rejected by Gurney (although in the writer's opinion it appears to be the better of the two values). Also included are fragment velocity data from a 4,000-pound bomb, and a 40-mm Bofors shell; the C/M of the bomb was determined for the cylindrical midsection, that for the Bofors shell by taking the ratio of filling weight to weight of the empty unfuzed shell. Rejecting the data on the Bofors shell as being improper in its C/M value, and rejecting the replicated data point on the 2-inch cylinder that was accepted by Gurney (as yielding a value of $\sqrt{2E}$ that is much farther from the average of the others) and accepting the replicate that Gurney rejected, there are six data points ranging in C/M value from 0.165 to 5.62. The mean value of $\sqrt{2E}$ calculated by Gurney's formula from this data on TNT is 7,731 ft/sec. Gurney gave the representative value as 8,000 ft/sec with a standard deviation of 470 ft/sec or 6.1% of the mean. The mean value of V_c calculated from this same data by Eq. (2) is 7,541 ft/sec with a standard deviation of 436 ft/sec or 5.8%. The slightly smaller deviation from the mean for the values of V_c is regarded by the writer as a feeble indication of the superiority of Eq. (2) as a scaling law over the original Gurney equation. Data of greater precision are needed to give a really clear indication on this point.

Held measured fragment velocities by flash X-ray, but, unfortunately, he does not state his results in digital form. To scale his graphs offers little hope of obtaining data of any value; he gives an equation but it is patently in error. Henry does not give any fragment velocity at all in support of his scaling law.

THE BUMBLEBEE WARHEAD REPORT

R. K. Warner and E. L. Nooker of the Bumblebee Warhead Group (BBW), Applied Physics Laboratory, Johns Hopkins University, Silver Spring, Maryland, in an unofficial internal memorandum, proposed to H. S. Morton on 2 May 1953, that a series of cylindrical warheads be fired and fragment velocities be determined. This series of experiments was intended primarily to establish a scaling law for cylindrical warheads with axial cylindrical voids in the explosive, but solid warheads without axial voids were included for comparison, and near the end of test series a set of experiments with solid explosive loading in steel casings carefully machined to several different wall thicknesses was included.

Results of these tests were not published in formal reports, but were stated in a long series of unofficial internal memoranda known locally as "BBW Reports." The proposal referred to in the previous paragraph was made in Report No. BBW-284. In December 1965, 80 of these reports covering this test series were loaned to the Naval Ordnance Test Station (now the Naval Weapons Center (NWC)) by the Chief, Bureau of Naval Weapons, under transmittal, Serial No. 06505. Their unofficial status and general unavailability would render futile any listing of them as bibliographic references. Although published as Confidential, and many of them remain so, the information that has been abstracted from them and is given here, has been declassified.

Table 2 lists the serial numbers of the rounds fired and their most important features, along with the BBW Report numbers giving the data. In 17 cases the initial report on a fired round is followed by a second report (for example reports 295 and 295-A) giving "Second Velocity Readings" which are more detailed. Rounds 1 to 59, inclusive, are in a continuous series except that there is no report available on Round No. 56.

Nearly all the tests were fired at the Naval Proving Ground, Dahlgren, Virginia, except Rounds 57, 58, and 59 which were fired at the New Mexico Institute of Mining and Technology, Socorro, New Mexico, in 1960 and 1961. Arena firing methods were used with careful attention to detail, the fragment impacts being recorded photographically on flash targets at three or more baseline distances from the detonated cylinder. Assessment of the films seems to have been done at Applied Physics Laboratory, and data reduction was done also at that location. No clear statement was made regarding data reduction methods.

The writer is confused by many of the values of initial fragment velocity that were given. Table 3 shows the average velocities that were given for fragment flight to targets at three distances, for Round 1. The differences between values given in the two reports is understandable as due to the more detailed film reading reported in the second report, but the method of averaging the 60-foot readings in Report 295-A is not understood. In Report No. BBW-303 entitled "First Summary of 18" Hollow Warhead Program," the average flight-to-target velocities of Round 1 are given again, but the values are: to 40 ft - 8,130 ft/sec, to 60 ft - 7,430 ft/sec, and to 80 ft - 7,120 ft/sec. From these average flight velocities, a single value of average initial fragment velocity was derived by a method not fully disclosed and is given in this same Report No. 303 as averaged with the same parameters for Round 2 at a value for V_o of 9,000 ft/sec. However, in Report No. 351, "Second Partial Summary of 18" Diameter Hollow Warhead Firings," this same average initial velocity of Rounds 1 and 2 is given as 8,800 ft/sec and in Report 406, "Third Partial Summary of 18" Diameter Hollow Warhead Firings," it is given as 8,700 ft/sec.

TABLE 2. Initial Fragment Velocity Values.

Report No.	Round No.	OD, in.	% R	C/M	$L^{0.5}$	V_o, ft/sec	V_c, ft/sec	Remarks
295-295A	1	18	0	1.575	0.9725	9,217	9,478	
295-295A	2	18	0	1.538	0.9651	8,551	8,860	
296-296A	3	18	40	0.947	0.8163	6,101	7,474	
296-296A	4	18	40	0.927	0.8106	5,975	7,371	
297-297A	5	18	80	0.329	0.5333	3,306	6,199	"Spurious" detonation
297-297A	6	18	80	0.328	0.5326	3,327	6,247	Special detonation system
310-310A	7	18	80	0.336	0.5382	3,780	7,023	Special detonation system
317-317A	8	18	60	0.613	0.6915	4,956	7,167	
319-319A	9	18	60	0.641	0.7037	5,530	7,858	Single point detonation
320-320A	10	18	60	0.627	0.6977	5,204	7,459	
398	11	11 3/4	74	0.279	0.4541	2,870	6,320	
353-353A	12	18	0	1.575	0.9725	8.907	9,159	
350-350A	13	18	20	1.229	0.8952	7,370	8,233	
354-354A	14	18	60	0.649	0.7072	5,267	7,448	
396	15	7	70	0.1267	0.3453	2,257	6,536	
394	16	7	50	0.2326	0.4573	3,284	7,182	
389	17	7	30	0.3297	0.5338	4,273	8,005	
386	18	7	0	0.4835	0.6280	5,755	9,164	
393	19	7	50	0.2359	0.4602	3,554	7,723	
367,367A	20	11 3/4	0	0.836	0.7795	6,431	8,250	
408	21	12 3/4	0	0.486	0.6293	5,365	8,525	
409	22	12	0	0.622	0.6955	6,005	8,634	3/4-inch wall
375,375A	23	11 3/4	44	0.473	0.6223	4,740	7,617	
369,369A	24	11 3/4	22	0.663	0.7132	6,089	8,536	
368,368A	25	11 3/4	0	0.801	0.7671	6,692	8,724	
410	26	12 3/4	0	0.485	0.6288	5,428	8,632	1-inch wall
362,362A	27	18	20	1.259	0.9027	7,226	8,005	

TABLE 2. (Cont'd).

Report No.	Round No.	OD, in.	% R	C/M	$L^{0.5}$	V_o, ft/sec	V_c, ft/sec	Remarks
399	28	11 3/4	74	0.230	0.4550	2,930	6,440	
374-374A	29	11 3/4	44	0.487	0.6299	4,756	7,550	
370-370A	30	11 3/4	22	0.646	0.7057	5,636	7,984	
383	31	7	0	0.4877	0.6302	5,762	9,143	
387	32	7	30	0.3312	0.5348	4,370	8,171	
395	33	7	70	0.1350	0.3431	2,378	6,931	
392	34	7	50	0.2425	0.4660	3,536	7,588	
382	35	7	0	0.4895	0.6312	5,527	8,756	
391	36	7	30	0.3296	0.5337	4,223	7,913	
397	37	7	70	0.1280	0.3470	2,455	7,975	Single point detonation
405	38	18	60	0.619	0.6941	4,794	6,907	Single point detonation 1-inch airgap opposite
403	39	12	0	0.598	0.6847	5,937	8,671	3/4-inch wall
390	40	18	60	0.653	0.7089	5,306	7,485	Diffuser tube, single point detonation
407	41	11 3/4	60	0.329	0.5332	3,887	7,290	Tiny Tim motor tube
411	42	7	0	0.5989	0.6851	5,312	7,754	1 1/2 L/D - 0.500 wall[a]
412	43	7	0	0.6014	0.6862	4,961	7,230	1 L/D - 0.500 wall[a]
413	44	7	0	0.5625	0.6680	4,489	6,720	1/2 L/D - 0.500 wall[a]
414	45	7	0	0.4244	0.5948	5,009	8,421	Machined OD 0.687[a]
415	46	7	0	0.2971	0.5100	4,248	8,329	Machined OD 0.937[a]
416	47	7	0	0.8889	0.7975	6,565	8,232	Machined OD 0.343[a]
417	48	7	0	1.6410	0.9853	8,161	8,283	Machined OD 0.187[a]
418	49	7	0	0.6015	0.6863	4,487	6,538	1/2 L/D - 0.500 wall[a]
419	50	7	0	0.2969	0.5099	4,173	8,184	Machined OD 0.937[a]
420	51	7	0	0.6034	0.6871	4,906	7,140	1 L/D - 0.500 wall[a]
421	52	7	0	0.6060	0.6883	5,400	7,845	1 1/2 L/D - 0.500 wall[a]

TABLE 2. (Cont'd).

Report No.	Round No.	OD, in.	% R	C/M	$L^{0.5}$	V_o, ft/sec	V_c, ft/sec	Remarks
422	53	7	0	0.4217	0.5932	4,944	8,334	Machined OD 0.687[a]
423	54	7	0	0.8897	0.7978	6,539	8,196	Machined OD 0.343[a]
424	55	7	0	1.6440	0.9861	8,248	8,364	Machined OD 0.187[a]
	56							Cannot find
589	57	7	0	0.6024	0.6867	6,101	8,885	6 L/D - 0.500 wall[a]
590	58	7	0	0.6231	0.6960	5,347	7,682	1 1/2 L/D - 0.500 wall[a,b]
591	59	7	0	0.6213	0.6950	5,641	8,117	1 1/2 L/D - 0.500 wall[a,b]

[a] Cavity Paint only - no hot melt.
[b] Composition H-6 explosive.

TABLE 3. Average Velocities in Ft/Sec at Three Distances for Round 1.

Distance, ft	Report 295	Report 295A		
40	8,170	8,160		
			8,090	
	8,070	8,020		
60	7,470	7,360		
			7,330	
	7,530	7,260		
				7,300
	7,450	7,310		
			7,270	
	7,310	7,190		
80	7,120	7,070		
			7,025	
	7,120	6,980		

In view of this evident confusion, the writer developed his own value for initial fragment velocity for each round. The main values for average velocity to targets at three or more distances were taken wherever possible from the reports giving "Second Velocity Readings." The differences between logarithms of these mean velocities (usually three distances and three differences) gives values of logarithmic decrement in velocity, the average of which for each round is applied to each mean velocity-distance datum to give three values of initial velocity at detonation. The latter values are averaged for each round and are given in Table 2 as values of V_o. It may be noted that the values of V_o derived by the writer for Rounds 1 and 2 average 8,884 ft/sec, which is closer to the value of 9,000 ft/sec given in Report BBW-303 than it is to the values given in the two later "Partial Summary" reports.

There is also some confusion as to the values of C/M for the fired rounds. The design figure for Round 1 was 1.72; in Report BBW-303 the "actual C/M" is stated to be 1.665; in Reports BBW-351 and -406 the value 1.73 is shown for this round. Weights of Cavity Hot Melt (asphaltic) are given in most cases, and are as great as 10% of the weight of the explosive, but no part of this weight was included with the explosive in determining C/M. Consequently the writer has calculated the values of C/M that are shown in Table 2 estimating the weight of the end cap and subtracting it from the stated explosive weight, and adding to the explosive weight one-half of the stated weight of the Cavity Hot Melt (in view of its gas-producing capability).

In further explanation of Table 2, the figures given as %R refer to the weight percent (W/%) of explosive removed from each round in forming the axial cylindrical hole; thus, a round stated as having 0%R is solidly and fully loaded with explosive, and one given as 80%R has in it an axial cavity so large that only 20% of the total possible weight of explosive has been loaded into it. The values of $L^{0.5}$ and V_c were calculated by the writer on the basis of Eq. (2), using the values of C/M and V_o given in Table 2.

In the "Remarks" column of Table 2 it may be noted that Round 5 is listed as having "Spurious Detonation", and that Rounds 6 and 7 are replicates of it. In Report BBW-297 the statement appears that "A 'spurious' or 'unusual' high order detonation was obtained in Round 5; Round 6 was thought to be a 'normal' high order". The introduction of Report BBW-310, reporting data on Round 7 states in full:

> "This round was fired in an attempt to explain the apparent anomaly in the initial velocity obtained with the other two 80 percent HE removed warheads (Rounds 6 and 7). In these two preceding rounds the initial velocity was considerably higher than expected, the irregularity being attributed to an abnormalcy in the detonation wave(s) formed. This third round used a different detonation system which was believed would eliminate the detonation wave trouble and perhaps yield the expected initial velocity."

In a number of cases, rounds are listed as having single-point detonation. In these cases, the round was inverted and the detonator was applied to the inside cylindrical surface of the thin liner covering the Composition B explosive at the end opposite the cast Composition B end cap. For rounds not noted in this manner, detonation was at the center of the cast Composition B end cap, proceeded at first radially in the rounds with axial voids, and then normally down the length of the round.

Wall thickness (of the outer metal casing) is given in some cases. Round 38 had a longitudinal airgap in the explosive opposite the single-point of detonation. For Round 40, the axial cavity was lined with a diffuser tube structure such as was specified for the TALOS warhead assembly; in other cases the hollow warheads had aluminum liners of unspecified thicknesses. Round 41 had a metal jacket made from low alloy steel (about 0.40 carbon, 1.7 manganese, 0.50 molybdenum) instead of the mild steel used for the other rounds. The cavity paint was specified as being about 0.002 inch thick.

THE BUMBLEBEE WARHEAD TEST RESULTS

VARIED WALL-THICKNESS SERIES WITH L/D OF 2 1/2

There are several clearly defined test series within the total assemblage of tests set forth in Table 2, of which the series of greatest interest to the writer was fired almost at the end of the Project. The rounds numbered 45 through 48 inclusive, 50, and 53 through 55 inclusive are a series in which the mild steel cases were carefully machined to specified wall thicknesses ranging from 3/16 to 5/16 inch and were coated inside with 0.002-inch-thick cavity paint (not hot melt) before loading with Composition B by liquid pour (not pellet loading). The values of C/M ranged from 0.297 to 1.64, so this group may be regarded as providing experimental data suitable for testing a scaling law. In Table 4 the scaling law expressed by Eq. (2) is tested by this data, except that in addition to the exponent used in Eq. (2) several others differing slightly from 0.5 are tried.

A specific conclusion which may be drawn from the data in Table 4 is that this family of data points is best represented by a scaling law which varies slightly from Eq. (2) in that an exponent near 0.496 gives V_c values varying less from their mean than when the exponent is 0.500. The range of test conditions covers about a fourfold range of C/M values, and the series consists of only eight shots, so this data cannot be regarded as an extensive or exhaustive test of the scaling law; however, the fact that the minimum sigma is only slightly greater than 1% of the mean is testimony to the care with which the tests were conducted and the data were gathered. The writer regards this set of data as the strongest evidence now available in support of the scaling law of Eq. (2).

The last column in Table 4 giving values of $\sqrt{2E}$ was calculated using the Gurney equation. When tested as a scaling law by this data, its deficiency is seen to be not very great, indeed its deficiencies do not become troublesome until values of C/M considerably above those represented by this data are reached.

It should be noted that exponents other than 0.5 are used only in Table 4 in this report and in discussions of future work; all other uses of Eq. (2) presume that the exponent in it is 0.5. It may also bear repeating that all values of Characteristic Velocity, V_c, given throughout this report have been calculated using Eq. (2).

TABLE 4. Varied Wall-Thicknesses.

Round No.	V_o, ft/sec	C/M	V_o (ft/sec for variations of Eq. (2)[a]					$\sqrt{2E}$
			0.490	0.493	0.496	0.500	0.510	
45	5,009	0.4244	8,344	8,361	8,387	8,421	8,510	8,465
46	4,248	0.2971	8,218	8,250	8,284	8,329	8,442	8,442
47	6,565	0.8889	8,195	8,206	8,218	8,232	8,369	8,368
48	8,161	1.641	8,283	8,284	8,284	8,285	8,288	8,596
50	4,173	0.2969	8,076	8,109	8,142	8,186	8,298	8,208
53	4,944	0.4217	8,248	8,274	8,301	8,334	8,422	8,378
54	6,539	0.8897	8,159	8,171	8,182	8,196	8,233	8,333
55	8,248	1.644	8,362	8,363	8,363	8,364	8,367	8,683
	Average V_c		8,234	8,252	8,270	8,293	9,354	8,423
	σ, (ft/sec)		90.7	85.5	84.1	86.0	102.3	149.0
	σ, % of Av.		1.10	1.04	1.02	1.04	1.22	1.77

[a]Eq. (2, rearranged) $V_c = V_o \ln (1 + C/M)^{-0.5}$, and its variations employ substitutions of the values shown as exponents of the bracketed term.

VARIED L/D RATIO SERIES

A second series of tests with machined OD warheads all having 0.500-inch thickness was made with various values of L/D ratio from 1/2 to 6. Rounds numbered 42, 43, 44, 49, 51, 52, and 57 are clearly members of this series; since no member of the varied wall-thickness series has a wall-thickness of 0.500 inch, the intention of the planners of these series is not quite clear. However, it has just been shown that the wall-thickness series gave Characteristic Velocity values all closely clustering about their mean with substantially no trend attributable to wall-thickness variation, so it is concluded that this mean value can be validly considered to represent the L/D value of 2 1/2 in the present series. There is only one round with L/D of 6, and none in the interval between 2 1/2 and 6, which is fortunate, particularly because the entire plan of the BBW warhead firings was predicated upon the assumption that an L/D ratio of 2 1/2 would be sufficient to "minimize" end effects. More rounds fired with L/D greater than 2 1/2 would have more effectively tested this assumption. As in the previously discussed series all warheads were coated inside with 0.002 inch of cavity paint instead of hot melt, and were loaded by pouring Composition B without use of pellets.

The Characteristic Velocity values for this series are shown in Fig. 2. The trend of increasing values of Characteristic Velocity with increasing values of L/D in shorter, fatter cylinders is not surprising; the tendency of the curve to continue rising beyond L/D 2 1/2 will seem surprising to some however. The single point at L/D = 6 (8,885 ft/sec) does not seem to the writer to be out of line, though, when compared with the values computed by the writer from data determined by cylinder expansion using 1.0-inch ID copper cylinders 12 inches long, and reported in the Fourth Detonation Symposium (8,880 ft/sec from data by Kury (Ref. 9) and 9,016 ft/sec from data by Hoskin, et al (Ref. 10).

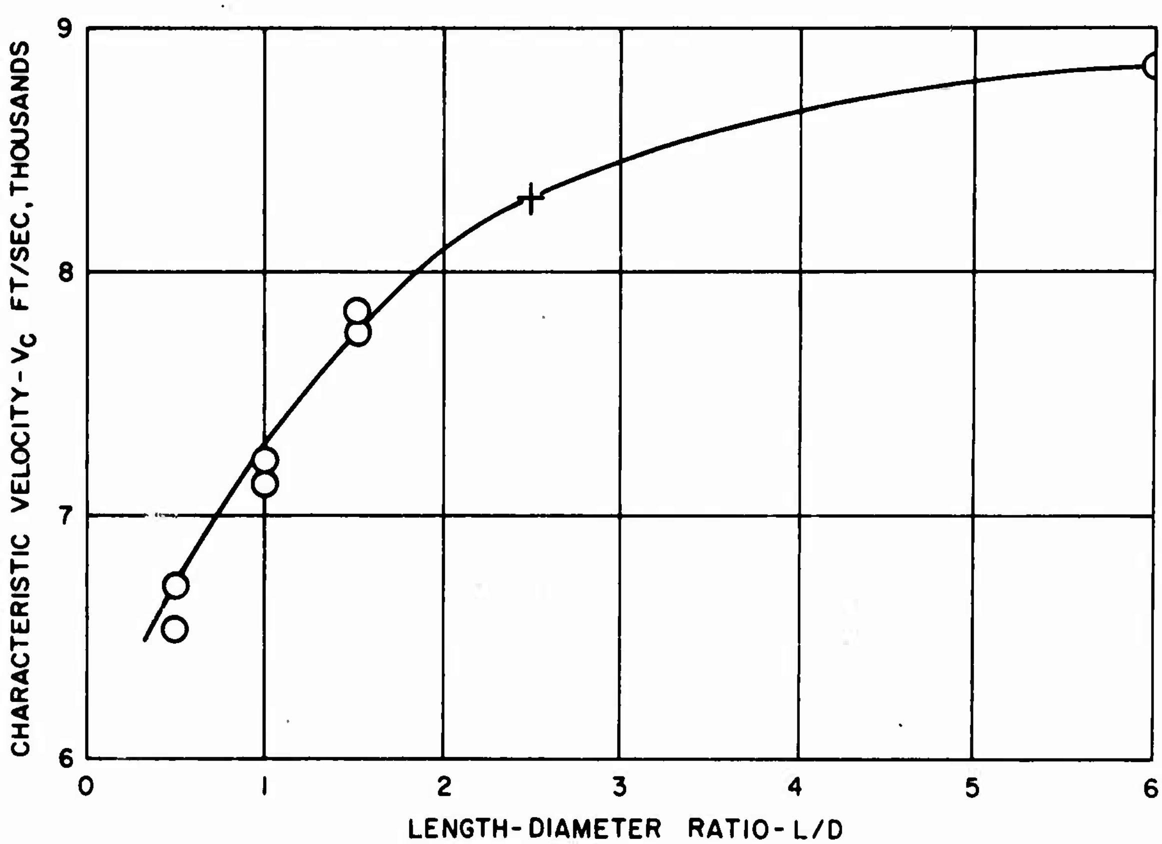

FIG. 2. L/D Series - BBW Reports Plus Average of Varied Wall-Thickness Series.

VARIED PERCENT-OF-EXPLOSIVE-REMOVED SERIES

The warhead firing program reported in the BBW Warhead Report series was initiated for the purpose (as stated in BBW Report 280) of investigating a preliminary finding from Dahlgren that the removal of explosive to create an extra cylindrical hole in a cylindrical warhead did not reduce the fragment velocity in proportion to the reduction in explosive weight. From this standpoint, then, the percent-of-explosive-removed (% R) series, carried out in 7- , 11 3/4- , and 18-inch diameters, was the principal object of the BBW project. They were all fired with steel casings unmachined on the OD and coated inside with several pounds of asphaltic "Cavity Hot Melt" before pelletized loading with Composition B. All had an explosive end cap which in some cases was placed uppermost and was centrally detonated, while in other cases the end cap was placed beneath and the round was "Single-Point" detonated near its upper end by a small mass of plastic explosive in contact with the inner liner. No significant difference in results has been seen by the writer in the results for rounds detonated by these two procedures, so this factor has been ignored. Hollow warheads were all but one lined with thin sheet aluminum.

The 0% R rounds are those with solid explosive and may be regarded as equivalent to conventional warheads fired for comparison. Looking first at them separately, we see that in addition to the rounds of the sizes just mentioned there are two each of 12- and 12 3/4-inch diameter; all shown in Table 5. The averages of Characteristic Velocity for each size are shown in the Table, and it can be seen that there is no consistent diameter effect. Consequently, the overall average is taken and has a standard deviation of 342 ft/sec. This mean value and its standard deviation are plotted in Fig. 3 on the ordinate of 0% R, in comparison with the mean value found in the Varied Wall-Thickness Series, Table 4, and its standard deviation. Clearly, the data from Table 5 are more variable. The difference between the two means is about 6.5% and no reason for it can be given with assurance; the lower value is associated with careful machining of the OD of the cases and with the use of very thin Cavity Paint instead of Cavity Hot Melt. The writer's inclusion of one-half of the weight of Cavity Hot Melt in the weight of the explosive is, perhaps, not very firmly grounded, but to remove this element of "explosive" weight would reduce the values of C/M and increase the difference seen here. It may also be noted that V_c from the Solem and Singleton data at C/M = 1.0 as plotted in Fig. 1 of this report agrees well with the mean from the Varied Wall-Thickness series, as may be seen in Fig. 3.

TABLE 5. Unmachined Cases - Solid Explosive.

Round No.	OD, in.	V_c, ft/sec	V_c group average
1	18	9,478	
2	18	8,860	
12	18	9,159	9,166
20	11 3/4	8,250	
25	11 3/4	8,724	8,487

TABLE 5. (Cont'd).

Round No.	OD, in.	V_c, ft/sec	V_c group average
21	12 3/4	8,525	
26	12 3/4	8,632	8,578
22	12	8,634	
39	12	8,671	8,652
18	7	9,164	
31	7	9,143	
35	7	8,756	9,021
		Average	8,833
		σ = 342 (3.9% of Average)	

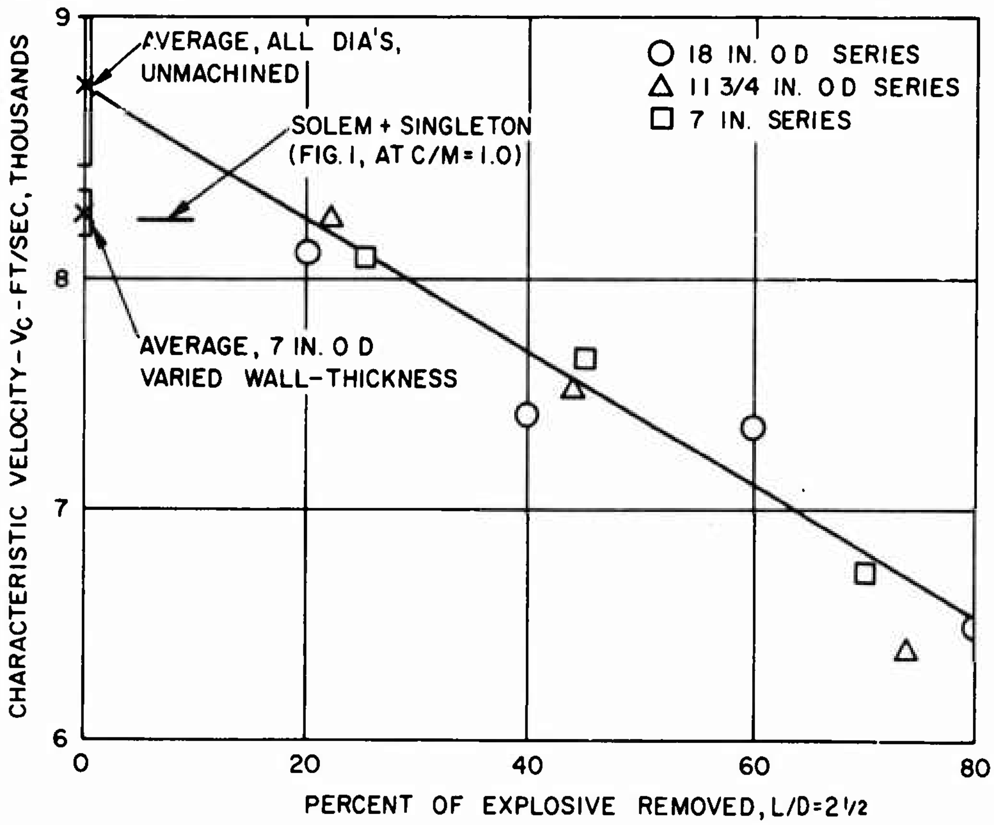

FIG. 3. Varied Percent-of-Explosive-Removed Series.

The fact that no significant diameter effect is shown in Table 5 is also regarded as a point in justification of the treatment of the remaining data in this Percent-of-Explosive-Removed series as though the three diameters tested were all substantially equivalent when the data is reduced to Characteristic Velocities. This has been done in plotting

Fig. 3. Here the data out to a value of 80% Removed appear to be correlateable within their general accuracy by a straight line originating at the average value for 0% Removed found in Table 5. The points shown are nearly all average values of two rounds, but the value at 80% is an average for three and the point at 60% was replicated six times. The existence of a true straight line relation out to a value of 80% Removed is undoubtedly open to question and future determination by more accurate means; extrapolation beyond 80% is also subject to future determination.

It is concluded, however, that the axially hollow warhead can be reasonably well scaled using Eq. (2), with adjustment of the Characteristic Velocity as shown in Fig. 3. Extrapolation of the line in Fig. 3 to some finite value of Characteristic Velocity at 100% Removed does not imply that a warhead without any explosive will still give some fragment velocity, because Eq. (2) predicts zero fragment velocity when the value of C/M is zero, regardless of the value of the Characteristic Velocity.

INDIVIDUAL EXPERIMENTS

A few rounds in the BBW tests were deviant in some special characteristic and should be considered individually. For instance, Round No. 38 was 18 inches in diameter, with 60% of its explosive removed, but in addition to being detonated at a "Single-Point" as has been previously discussed, the explosive had a longitudinal airgap 1 inch wide opposite the point of detonation. The Characteristic Velocity that was determined from its firing, 6,907 ft/sec, was not unusual in comparison with other 18-inch rounds, as may be seen in Fig. 3; thus, it requires no further notice. Round No. 40, also 18 inches in diameter with 60% of its explosive removed was lined on the inner face of the explosive by a diffuser tube "similar to that used in the TALOS (61 b) warhead assembly." The Characteristic Velocity calculated from the data on this round is 7,485 ft/sec, which is a little on the high side of the average for the 18-inch, 60% R rounds, but is well within the normal dispersion of the data for the similar rounds with aluminum liners.

Round No. 41 was 11 3/4 inches in diameter with 60% explosive removed, but instead of having a steel jacket made from "mild steel" as were all the others, its jacket was made from the motor tube for a Tiny Tim rocket, which was alloy steel with about 40 points carbon, 1.69% manganese and 0.49% molybdenum. The Characteristic Velocity was calculated as 7,290 ft/sec; this result is again in no way remarkable.

The last in the list, Round No. 58 and 59 were loaded with H-6 explosive rather than Composition B, and has an L/D ratio of only 1 1/2. Their average Characteristic Velocity is 7,900 ft/sec, which is a little above the curve in Fig. 2 for estimating the Characteristic Velocity for H-6 at other values in L/D ratio should be contemplated with caution.

POSSIBILITIES FOR FUTURE INVESTIGATION

STUDIES OF L/D RATIO

A great deal of fragment velocity data and many Gurney constant determinations have been taken on cylinders having an L/D ratio of 2 1/2, under the assumption that this condition is adequate to avoid problems arising from end effects in detonation. Most of the BBW data was so taken, as was most of the Solem and Singleton (Ref. 7) data. However, Fig. 2 of this report indicates that this assumption may be much less well founded than has been assumed, and that the decision of Kury (Ref. 10), and others, and of Hoskin (Ref. 10), and others to conduct cylinder tests at an L/D ratio of 12 may be much more realistic.

The cylinder expansion data at NWC will probably be taken at an L/D of 12 for some time into the forseeable future. If this is so, the basic data on the Characteristic Velocity (or the Gurney constant) of explosives is accumulated under these conditions, it will be quite desirable to investigate carefully the entire range of end effects in order to be able to dependably translate this basic explosive data into warhead fragment velocities. Some of the present disarrangements in Gurney constant values may be cleared up in the process.

FLAT PLATES DRIVEN BY TANGENTIAL DETONATION

Since the Fourth Detonation Symposium, 12-15 October 1965, Naval Ordnance Laboratory, White Oak, Maryland, the writer has been intrigued by the "open-face-sandwich" data given by Hoskin (Ref. 10), and others. They used plates of mild steel, aluminum, brass and copper and a fairly wide range of values of C/M, and determined normal velocities with a precision of about 1%. Fitting their data by least squares they obtained the following equation, in which V_n is the normal velocity while V_c and C/M are as defined previously:

$$V_n = V_c \frac{C/M}{C/M + 2} \qquad (6)$$

the value of V_c being 4.46 mm/μsec, for Composition B.

Deriving values of V_n corresponding to specific values of C/M from Eq. (6), the writer entered this data in several variations of Eq. (2) in order to find the exponent (in the same manner as in Table 4) giving the lowest standard deviation in V_c. The minimum was found for an exponent of 0.985 which is very near the round figure of 1.0. This would point toward the possibility that metal velocities for the edge-detonated open-face-sandwich might be dependably correlated by a variation of Eq. (2) using the term L in place of $L^{0.5}$. It may be noted that when Eq. (2) is modified in this way it becomes exactly analogous to the rocket propulsion equation previously mentioned. (Values of L corresponding to values of C/M are shown in the Appendix.) The values of V_c obtained from the Hoskin data and Eq. (2) with exponent 1.0, average 7,087 ft/sec (2,160 m/sec), which is in the range of values which may be found by more careful experimentation to be the value reached by extrapolation to 100% of Explosive Removed in the hollow warhead type of test exemplified by Fig. 2. This latter type of test is a cylindrical analogue of the flat plate test. Future investigation is called for and could very possibly reveal a useful relation between the cylinder expansion and flat plate experimental data for predicting metal velocity.

SPHERICAL WARHEADS

Fragment velocities for 12-inch ID, 1/4-inch-thick aluminum hemispheres accelerated by spheres of PBX-9404 and LX04-01 and observed with streak camera have been reported by Wilkins (Ref. 11), and the slopes of the curve for explosive in contact with the metal shell have been used by the writer to determine the Gurney $\sqrt{2E}$ (using Gurney's sphere equation)(Ref. 3) and the Characteristic Velocity V_c using Eq. (2), for the two explosives. The value of C/M was over 5.0.

The same explosives were included in data reported from the same laboratory by Kury (Ref. 9) and others, using the cylinder expansion test at C/M values of about 0.5 - that is roughly one-tenth those for the spherical shots. For each explosive they report metal velocities at two radii, the smaller radius they consider as representative of head-on detonation impact, as would be the case in the spherical geometry, while the larger velocity is characteristic of the detonation front moving parallel to the wall as in the cylinder expansion test. Using the smaller velocities for the two explosives and calculating the Gurney $\sqrt{2E}$ and the V_c we have the information shown in Table 6.

Obviously the problem of scaling fragment velocities between two experiments differing in C/M by a factor of 10 is a difficult one, and while the performance of Eq. (2) is better than that of the Gurney sphere formula, it is not very good. The question is raised, however, as to whether there is a possibility that when sufficient data is at hand from spherical expansion tests, an exponent might be found which would give a variation of Eq. (2) which would make it a really good scaling law for spherical warheads.

TABLE 6. Comparative Values and Differences in Wilkins and Kury Data.

	PBX 9404-03	LX04-01
Values of $\sqrt{2E}$ from Wilkins data, ft/sec	10,886	10,453
" " " " Kury " "	8,521	8,048
Differences	2,365	2,405
Differences, percent of Wilkins data	21.7	23.0
Values of V_c from Wilkins data, ft/sec	9,531	9,006
" " " " Kury " "	8,314	7,848
Differences	1,217	1,158
Differences, percent of Wilkins data	12.8	12.9

Appendix

VALUES OF C/M AND CONVERSION FACTORS

Table 7 of this Appendix gives values of L and $L^{0.5}$ for corresponding values of C/M, for use in connection with Eq. (2). Figure 4 shows values of the conversion factor which may be used to convert values of $L^{0.5}$ to values of $\sqrt{R}$, for use in Gurney's cylinder equation.

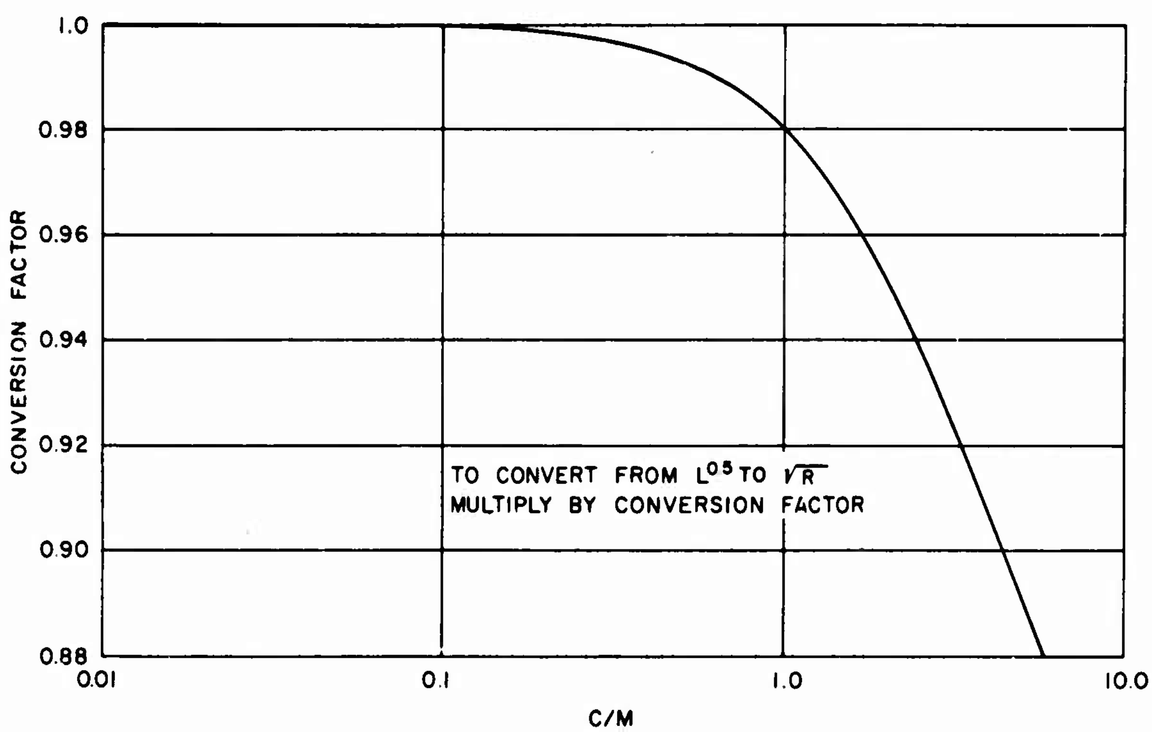

FIG. 4. Conversion Factor Values for Use in Gurney's Cylinder Equation.

TABLE 7. Values of L and $L^{0.5}$ $[L = \ln(1 + C/M)]$.

C/M	L	$L^{0.5}$	C/M	L	$L^{0.5}$	C/M	L	$L^{0.5}$
0.00	0.00000	0.00000	0.35	0.30010	0.5478	0.70	0.53062	0.7284
0.01	0.00995	0.09975	0.36	0.30748	0.5545	0.71	0.53649	0.7324
0.02	0.01980	0.1440	0.37	0.31481	0.5611	0.72	0.54232	0.7364
0.03	0.02955	0.1719	0.38	0.32208	0.5675	0.73	0.54812	0.7404
0.04	0.03922	0.1980	0.39	0.32930	0.5739	0.74	0.55388	0.7442
0.05	0.04879	0.2209	0.40	0.33647	0.5801	0.75	0.55961	0.7480
0.06	0.05826	0.2414	0.41	0.34358	0.5861	0.76	0.56531	0.7518
0.07	0.06765	0.2601	0.42	0.35065	0.5922	0.77	0.57097	0.7556
0.08	0.07696	0.2774	0.43	0.35767	0.5981	0.78	0.57661	0.7594
0.09	0.08617	0.2935	0.44	0.36464	0.6039	0.79	0.58221	0.7631
0.10	0.09531	0.3087	0.45	0.37156	0.6096	0.80	0.58778	0.7667
0.11	0.10436	0.3230	0.46	0.37843	0.6152	0.81	0.59332	0.7703
0.12	0.11332	0.3366	0.47	0.38526	0.6207	0.82	0.59883	0.7738
0.13	0.12221	0.3496	0.48	0.39204	0.6261	0.83	0.60431	0.7774
0.14	0.13102	0.3620	0.49	0.39877	0.6315	0.84	0.60976	0.7809
0.15	0.13976	0.3738	0.50	0.40546	0.6367	0.85	0.61518	0.7844
0.16	0.14842	0.3852	0.51	0.41210	0.6419	0.86	0.62057	0.7878
0.17	0.15700	0.3962	0.52	0.41871	0.6471	0.87	0.62593	0.7912
0.18	0.16551	0.4068	0.53	0.42526	0.6521	0.88	0.63127	0.7945
0.19	0.17395	0.4171	0.54	0.43178	0.6571	0.89	0.63657	0.7978
0.20	0.18232	0.4270	0.55	0.43825	0.6620	0.90	0.64185	0.8011
0.21	0.19062	0.4366	0.56	0.44468	0.6668	0.91	0.64710	0.8044
0.22	0.19885	0.4459	0.57	0.45107	0.6716	0.92	0.65232	0.8077
0.23	0.20701	0.4550	0.58	0.45742	0.6763	0.93	0.65752	0.8109
0.24	0.21511	0.4638	0.59	0.46373	0.6810	0.94	0.66268	0.8141
0.25	0.22314	0.4724	0.60	0.47000	0.6856	0.95	0.66782	0.8172
0.26	0.23111	0.4807	0.61	0.47623	0.6901	0.96	0.67294	0.8203
0.27	0.23901	0.4889	0.62	0.48242	0.6946	0.97	0.67803	0.8234
0.28	0.24686	0.4968	0.63	0.48858	0.6990	0.98	0.68309	0.8265
0.29	0.25464	0.5046	0.64	0.49469	0.7033	0.99	0.68813	0.8295
0.30	0.26236	0.5122	0.65	0.50077	0.7076	1.00	0.69314	0.8325
0.31	0.27002	0.5196	0.66	0.50681	0.7119			
0.32	0.27763	0.5269	0.67	0.51282	0.7161			
0.33	0.28517	0.5340	0.68	0.51879	0.7203			
0.34	0.29266	0.5410	0.69	0.52472	0.7244			

TABLE 7. (Cont'd).

C/M	L	$L^{0.5}$	C/M	L	$L^{0.5}$	C/M	L	$L^{0.5}$
1.00	0.69314	0.8325	1.35	0.85442	0.9244	1.70	0.99325	0.9966
1.01	0.69813	0.8355	1.36	0.85866	0.9266	1.71	0.99695	0.9985
1.02	0.70309	0.8385	1.37	0.86289	0.9289	1.72	1.00063	1.0003
1.03	0.70803	0.8414	1.38	0.86710	0.9312	1.73	1.00430	1.0021
1.04	0.71294	0.8443	1.39	0.87129	0.9334	1.74	1.00796	1.0040
1.05	0.71783	0.8472	1.40	0.87547	0.9357	1.75	1.01160	1.0058
1.06	0.72270	0.8501	1.41	0.87963	0.9379	1.76	1.01523	1.0076
1.07	0.72754	0.8529	1.42	0.88377	0.9401	1.77	1.01885	1.0094
1.08	0.73236	0.8558	1.43	0.88789	0.9423	1.78	1.02245	1.0112
1.09	0.73716	0.8586	1.44	0.89200	0.9444	1.79	1.02604	1.0129
1.10	0.74193	0.8614	1.45	0.89609	0.9466	1.80	1.02962	1.0147
1.11	0.74668	0.8641	1.46	0.90016	0.9488	1.81	1.03318	1.0165
1.12	0.75141	0.8668	1.47	0.90422	0.9509	1.82	1.03674	1.0182
1.13	0.75612	0.8696	1.48	0.90826	0.9530	1.83	1.04028	1.0200
1.14	0.76080	0.8722	1.49	0.91228	0.9551	1.84	1.04380	1.0217
1.15	0.76546	0.8749	1.50	0.91629	0.9572	1.85	1.04732	1.0234
1.16	0.77010	0.8776	1.51	0.92028	0.9593	1.86	1.05082	1.0251
1.17	0.77472	0.8802	1.52	0.92426	0.9614	1.87	1.05431	1.0268
1.18	0.77932	0.8828	1.53	0.92822	0.9634	1.88	1.05779	1.0285
1.19	0.78390	0.8854	1.54	0.93216	0.9655	1.89	1.06126	1.0302
1.20	0.78846	0.8880	1.55	0.93609	0.9675	1.90	1.06471	1.0319
1.21	0.79299	0.8905	1.56	0.94001	0.9695	1.91	1.06815	1.0335
1.22	0.79751	0.8930	1.57	0.94391	0.9715	1.92	1.07158	1.0352
1.23	0.80200	0.8955	1.58	0.94779	0.9735	1.93	1.07500	1.0368
1.24	0.80648	0.8980	1.59	0.95166	0.9755	1.94	1.07841	1.0385
1.25	0.81093	0.9005	1.60	0.95551	0.9775	1.95	1.08181	1.0401
1.26	0.81536	0.9030	1.61	0.95935	0.9795	1.96	1.08519	1.0417
1.27	0.81978	0.9054	1.62	0.96317	0.9814	1.97	1.08856	1.0433
1.28	0.82418	0.9078	1.63	0.96698	0.9834	1.98	1.09192	1.0450
1.29	0.82855	0.9102	1.64	0.97078	0.9853	1.99	1.09527	1.0466
1.30	0.83291	0.9126	1.65	0.97456	0.9872	2.00	1.09861	1.0482
1.31	0.83725	0.9150	1.66	0.97833	0.9891			
1.32	0.84157	0.9174	1.67	0.98208	0.9910			
1.33	0.84587	0.9197	1.68	0.98582	0.9929			
1.34	0.85015	0.9220	1.69	0.98954	0.9948			

TABLE 7. (Cont'd).

C/M	L	$L^{0.5}$	C/M	L	$L^{0.5}$	C/M	L	$L^{0.5}$
2.00	1.09861	1.0482	2.35	1.20896	1.0995	4.50	1.70475	1.306
2.01	1.10194	1.0497	2.36	1.21194	1.1009	4.60	1.72277	1.313
2.02	1.10526	1.0513	2.37	1.21491	1.1022	4.70	1.74047	1.319
2.03	1.10856	1.0529	2.38	1.21788	1.1036	4.80	1.75786	1.326
2.04	1.11186	1.0544	2.39	1.22083	1.1049	4.90	1.77495	1.332
2.05	1.11514	1.0560	2.40	1.22378	1.1062	5.00	1.79176	1.339
2.06	1.11841	1.0575	2.41	1.22671	1.1076	5.10	1.80829	1.345
2.07	1.12168	1.0591	2.42	1.22964	1.1089	5.20	1.82455	1.351
2.08	1.12493	1.0606	2.43	1.23256	1.1102	5.30	1.84055	1.357
2.09	1.12817	1.0621	2.44	1.23547	1.1115	5.40	1.85630	1.362
2.10	1.13140	1.0637	2.45	1.23837	1.1128	5.50	1.87180	1.368
2.11	1.13462	1.0652	2.46	1.24127	1.1141	5.60	1.88707	1.374
2.12	1.13783	1.0667	2.47	1.24415	1.1154	5.70	1.90211	1.379
2.13	1.14103	1.0682	2.48	1.24703	1.1167	5.80	1.91692	1.385
2.14	1.14422	1.0697	2.49	1.24990	1.1180	5.90	1.93152	1.390
2.15	1.14740	1.0712	2.50	1.25276	1.119	6.00	1.94591	1.395
2.16	1.15057	1.0727	2.60	1.28093	1.132	6.10	1.96009	1.400
2.17	1.15373	1.0741	2.70	1.30833	1.144	6.20	1.97408	1.405
2.18	1.15688	1.0756	2.80	1.33500	1.155	6.30	1.98787	1.410
2.19	1.16002	1.0771	2.90	1.36098	1.167	6.40	2.00148	1.415
2.20	1.16315	1.0785	3.00	1.38629	1.178	6.50	2.01490	1.420
2.21	1.16627	1.0799	3.10	1.41099	1.188	6.60	2.02815	1.424
2.22	1.16938	1.0814	3.20	1.43508	1.198	6.70	2.04122	1.429
2.23	1.17248	1.0828	3.30	1.45861	1.208	6.80	2.05412	1.433
2.24	1.17557	1.0842	3.40	1.48160	1.217	6.90	2.06686	1.437
2.25	1.17865	1.0857	3.50	1.50408	1.226	7.00	2.07944	1.442
2.26	1.18173	1.0871	3.60	1.52606	1.235	7.10	2.09186	1.446
2.27	1.18479	1.0885	3.70	1.54756	1.244	7.20	2.10413	1.451
2.28	1.18784	1.0899	3.80	1.56862	1.252	7.30	2.11626	1.455
2.29	1.19089	1.0913	3.90	1.58924	1.261	7.40	2.12823	1.459
2.30	1.19392	1.0927	4.00	1.60944	1.269	7.50	2.14007	1.463
2.31	1.19695	1.0941	4.10	1.62924	1.276			
2.32	1.19996	1.0954	4.20	1.64866	1.284			
2.33	1.20297	1.0968	4.30	1.66771	1.291			
2.34	1.20597	1.0982	4.40	1.68640	1.299			

TABLE 7. (Cont'd).

C/M	L	$L^{0.5}$	C/M	L	$L^{0.5}$	C/M	L	$L^{0.5}$
7.50	2.14007	1.463						
7.60	2.15176	1.467						
7.70	2.16332	1.471						
7.80	2.17475	1.475						
7.90	2.18605	1.479						
8.00	2.19722	1.482						
8.10	2.20827	1.486						
8.20	2.21920	1.490						
8.30	2.23001	1.493						
8.40	2.24071	1.497						
8.50	2.25129	1.500						
8.60	2.26176	1.504						
8.70	2.27213	1.507						
8.80	2.28238	1.511						
8.90	2.29253	1.514						
9.00	2.30258	1.517						
9.10	2.31253	1.521						
9.20	2.32238	1.524						
9.30	2.33213	1.527						
9.40	2.34180	1.530						
9.50	2.35137	1.533						
9.60	2.36084	1.537						
9.70	2.37023	1.540						
9.80	2.37954	1.543						
9.90	2.38875	1.546						
10.00	2.39789	1.549						

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13. ABSTRACT

Existing scaling laws for the prediction of fragment velocities from cylindrical warheads are examined, and a new law is proposed. Tests of the new law are shown, using the best known fragment velocity data. The new law is used for correlating previously unpublished data on length-to-diameter ratio effects and on the behavior of axially hollow warheads. Possibilities for profitable future investigations are outlined in studies of length-to-diameter ratio effects, and in the use of modifications of the new scaling law for correlating "open-face-sandwich" plate velocity data and fragment velocities from spherical warheads.

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